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Optically induced hysteresis in a two-state quantum dot laser

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Quantum dot lasers can lase from the ground state only, simultaneously from both the ground and first excited states and from the excited state only. We examine the influence of optical injection at frequencies close to the ground state when the free-running operation of the device is excited state lasing only. We demonstrate the existence of an injection-induced bistability between ground state dominated emission and excited state dominated emission and the consequent hysteresis loop in the lasing output. Experimental and numerical investigations are in excellent agreement. Inhomogeneous broadening is found to be the underlying physical mechanism driving the phenomenon.

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One of the distinguishing features of quantum dot (QD) lasers is their ability to lase from multiple distinct energy states. As with conventional semiconductor lasers, these devices can emit from the ground state (GS). However, single-state lasing from the first excited state (ES) can also be observed, as can simultaneous two-state lasing from the GS and first ES [1,2]. Much attention is naturally focused on further improvements of laser performance. One of the most successful techniques to this end is optical injection, which has already been shown to enhance the performance of several laser systems. Light from one laser, called the master laser (ML), is injected into the cavity of another laser, called the slave laser (SL). With QD lasers operating from the GS only, excellent phase-locking stability has been demonstrated when subjected to optical injection of the GS—even at very low injection levels—making them perfectly suited to technologies that exploit this configuration. This behavior has been attributed to an increased damping of the relaxation oscillations, meaning that QD lasers display many of the features normally associated with optically injected class A lasers. [3–8]

Extensive work on optical injection into the GS of QD lasers has been carried out to date, revealing many interesting features beyond phase locking, including excitability, multistability, chaos, and bistabilities [4,5,9]. The vast majority of this work utilized QD lasers in which only the GS was lasing, far from the ES threshold onset. There are relatively few existing experimental studies in which one must take into account both the GS and the ES. One example relevant to the work in this Letter is the study of ultrafast switching between the GS and ES induced by injection into the GS when the free-running operation is ES lasing only [10]. Switching between the GS and the ES has also been reported for the feedback configuration [11] and for two-section passively mode-locked devices via current and voltage variations [12]. In this Letter, we present both a theoretical and experimental study of optical injection into a QD laser emitting from the ES only. The injected light is close to the wavelength of the GS. In particular, we demonstrate the existence of a bistability between GS emission and ES emission and consequent hysteresis in the lasing output revealed by sweeping the power of the ML up and down, close to the wavelength of the GS. Hysteresis and bistability often play an important role in optically injected lasers as has been demonstrated for different device configurations and materials [13–16].

The model used in this Letter is a generalization of an electron-hole asymmetry model [17], modified to include the injection terms and to include some complexities of phase-amplitude coupling in the inhomogeneously broadened QD material. It is to this phase-amplitude coupling that we ascribe the presence of the hysteresis.

The SL was a 0.6 mm long InAs QD laser similar to that used in the study of ultrafast state switching [10]. The threshold current of the GS of the laser was 34 mA at room temperature. At 60 mA, a second threshold appeared, above which simultaneous lasing of the GS and ES was observed. Finally, when the current was increased above 80 mA, the device lased from the ES only. This sequential change in the output is typical for short cavity QD lasers and has been previously reported experimentally [1,2,10] and theoretically [17,18]. The device was fabricated so that the emission from the GS was from a single (longitudinal) mode which we label the preferential mode. The emission from the ES was multimode with a spectral width of approximately 10 nm [19].

The experimental setup is presented in Fig. 1. The ML was a commercially available tunable laser with a linewidth less than 100 kHz and tunable in steps of 0.1 pm. An optical circulator was used to inject light from the ML to the SL through lensed fiber via a polarization controller to ensure that the polarization states of the ML and SL were identical. The output from the SL was collected at port 3 of the circulator and connected to a 50/50 fiber beam splitter. To analyze the GS and the ES signals independently, two tunable optical band pass filters were used, one in each output arm of the splitter. The outputs of both optical filters were then connected to fast photodiodes and a high-speed, real-time oscilloscope. The SL injection current was set to 84 mA. At this operating point, the device was lasing in the ES only with an ES to GS suppression ratio in excess of 30 dB. Optical injection of sufficient strength into the GS-induced suppression of the ES by ~40 dB in comparison to the free-running emission. The wavelength separation between the two states at this operating point was ~85 nm which corresponds to ~16 THz.

To analyze the coherence of the slave laser, a delayed self-heterodyne measurement was performed. Figure 2 shows three linewidth curves. The blue peak (dotted) shows the free-running measurement. In this case, the current was 40 mA, so the device was emitting from the GS. The linewidth was on the order of 1 MHz. The black (solid) curve shows the linewidth of the ML, resolution limited and less than 100 kHz. The red (dashed) shows the linewidth when undergoing injection-induced GS lasing. It matches quite well with the curve of the ML; in particular, the linewidth was again less than 100 kHz (resolution limited), a significant reduction on the free-running case. The conclusion is clear that the output of the slave laser is phase locked to that of the ML.

We fix the ML wavelength as follows. Firstly, the wavelength of the ML is set so that it is close to the preferential mode of the GS. Then a region of continuous wave, stable output of the device under injection is located and, within this region, we maximize the intensity of the SL. The following results are obtained for this maximum-intensity detuning.

An investigation of the injection-induced switching boundaries between the GS and the ES was performed by increasing and decreasing sweeps of the injection power of the ML and analyzing the output of both the GS and ES of the slave laser

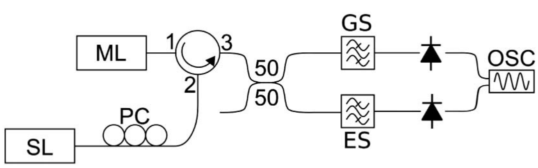

Fig. 1. Experimental setup used. ML, master laser; SL, slave laser; PC, polarization controllers. GS and ES indicate the filters used to separate the emissions in the ground state and the excited state. OSC, digital oscilloscope.

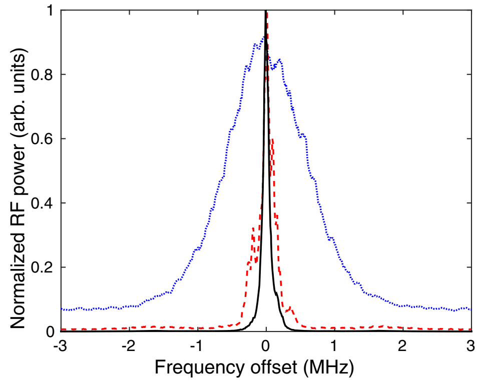

Fig. 2. Delayed self-heterodyne measurements of the linewidth. The dotted (blue) curve shows the free-running GS lasing linewidth at 40 mA. The dashed (red) curve shows the GS lasing linewidth when undergoing injection at 84 mA. The solid (black) curve shows the linewidth of the master laser.

on the oscilloscope. The ML power was swept with a step size of 100 μW in both directions. The average intensities of both the GS and the ES after each step in both directions were found and plotted as a function of the ML power as shown in Fig. 3. The solid lines represent the case of increasing ML power, while dashed lines represent the case of decreasing ML power. It should be noted that the ES intensity (blue) was lower than the GS intensity (red) due to higher losses in the filter centered at the ES emission. The actual intensities of both states were found to be of the same order when these losses were taken into account. Figure 3 takes this intensity correction into account. The figure clearly indicates that for a given injection sweep direction, there is an abrupt switch between the lasing states. However, this switch occurs at different ML powers, depending on the direction of the ML power sweep. That is, injection-induced hysteresis is clearly obtained. The inset of Fig. 3 shows two examples of time traces acquired at the same ML injection power of 0.4 mW, but for different directions of the power sweep. Panel (a) of the inset shows the case in which the ML power was decreasing, with a high suppression of the ES and injection-induced lasing of the GS observed. Panel (b)

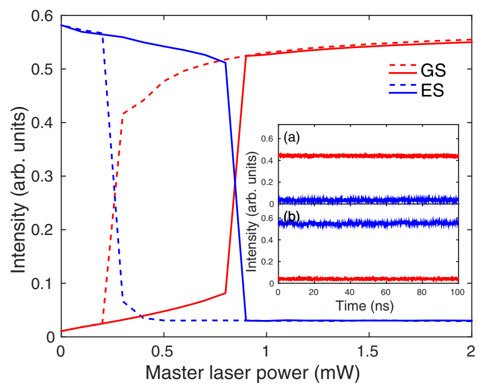

Fig. 3. Experimental results showing hysteresis. Solid lines show the intensities for increasing ML power, while the dashed lines show the intensities for decreasing ML power. The inset shows two traces for an ML power of 0.4 mW. In (a), the GS dominates; in (b), the ES dominates.

of the inset, on the other hand, shows a close to free-running emission intensity of the ES and very low emission at the GS wavelength. To characterize the hysteresis in Fig. 3, we measured the hysteresis loop area versus the slave laser pump current, finding an approximately linear increase over the tested range of 84–92 mA.

We also note that there are regions of simultaneous lasing in which emission from both states is possible. As the injected power is increased, the GS intensity rises slowly, while the ES intensity falls slowly until there is an abrupt change at an ML power of approximately 0.8 mW. On the other hand, as the injected power is decreased, the GS intensity falls slowly, but this is not accompanied by an appreciable increase in the ES intensity. The GS is always single mode throughout.

At this maximum-intensity detuning point, dynamical instabilities were noticeably absent, except at the GS switch off/ES switch on point in the case of the direction of decreasing injection strength in which both time traces (GS and ES) exhibited small bursts in intensity. Such injection-induced dynamical regimes lie outside the remit of this Letter and are not considered here.

To model the experimental results, we use a rate equation model tailored explicitly for QD lasers consisting of five equations for the complex electric field of the GS (E_g), the intensity of the ES (I_E), the occupation probabilities of the GS (n^g) and ES (n^e), and the carrier density in the wetting layer (n^w):

$$\dot{E}_g = \frac{1}{2}[(1 + i\alpha)(2g_0^g(n_e^g + n_h^g - 1) - 1) + i4\beta g_0^e(n_e^e + n_h^e - 1)]E_g + i\Delta E_g + \varepsilon, \quad (1)$$

$$\dot{I}_e = [4g_0^e(n_e^e + n_h^e - 1) - 1]I_e, \quad (2)$$

$$\dot{n}_{e,h}^g = \eta[2B_{e,h}n_{e,h}^e(1 - n_{e,h}^g) - 2C_{e,h}n_{e,h}^g(1 - n_{e,h}^e) - n_e^g n_h^g - g_0^g(n_e^g + n_h^g - 1)I_g], \quad (3)$$

$$\dot{n}_{e,h}^e = \eta[-2B_{e,h}n_{e,h}^e(1 - n_{e,h}^g) + C_{e,h}n_{e,h}^g(1 - n_{e,h}^e) + B_{e,h}^w n_{e,h}^w(1 - n_{e,h}^e) - C_{e,h}^w n_{e,h}^e - n_e^e n_h^e - g_0^e(n_e^e + n_h^e - 1)I_e], \quad (4)$$

$$\dot{n}_{e,h}^w = \eta[J - n_e^w n_h^w - 4B_{e,h}^w n_{e,h}^w(1 - n_{e,h}^e) + 4C_{e,h}^w n_{e,h}^e]. \quad (5)$$

The subscripts e and h stand for electron and hole respectively; the dot indicates differentiation with respect to $t \equiv t'/\tau_{\text{ph}}$, where t' is time and τ_{ph} is the photon lifetime. $\eta \equiv \tau_{\text{ph}}\tau^{-1} \ll 1$, where τ denotes the carrier recombination time. The factors 2 and 4 account for the spin degeneracy and confinement in the quantum dot energy levels. We define $g_0^g = g_0^e = g$ as the effective gain factor scaled to the cavity losses, and assume the gain factors and the cavity losses to be identical for both GS and ES. The terms $(1 - n_{e,h}^{g,e})$ describe Pauli blocking. $B_{e,h}$ and $B_{e,h}^w$ determine the capture rates to the GS and ES, correspondingly. To determine the escape rates $C_{e,h}$, we use the Kramers relation [17] linking the capture $B_{e,h}$ and the escape $C_{e,h}$ rates:

$$C_{e,h} = B_{e,h}\exp(-\Delta E_{e,h}/k_B T), \quad (6)$$

where k_B is the Boltzmann constant, and T the plasma temperature. We assume the GS and ES spacing as $\Delta E_e \simeq 50$ meV and $\Delta E_h \simeq 0$ meV. At room temperature, $k_B T = 25$ meV. J is the pump current, and α is the standard phase-amplitude coupling (the linewidth enhancement factor) in the GS. ε is the injection strength, and Δ is the detuning between the injected light and the GS emission. We consider zero detuning only ($\Delta = 0$). For the ES, only the intensity equation is considered since the ES phase is coupled neither to the injection nor to the GS.

Our rate equation model considers only one QD ensemble. Inhomogeneous broadening could be incorporated using much more complex models with separate equations for each ensemble such as in [20] leading to a much more complicated system. Rather than attempting quantitative agreement, we prefer to focus on the physics of the problem, so we qualitatively introduce some of the effects of inhomogeneous broadening via the empirical term β. This term enters the equations as a phase-amplitude coupling between the GS and the ES (see [21] for a similar introduction of phase-amplitude coupling to mimic inhomogeneous broadening). Phase-amplitude coupling terms typically describe the refractive index variation in a semiconductor material with changing carrier density. One of the characteristic features of inhomogeneous broadening is that even though an ensemble might not be contributing to lasing, its changing carrier density can still affect the refractive index. In particular, ensembles that would preferentially contribute to lasing at the ES can affect the GS lasing, even when the ES is off. Thus, β accounts for the phase-amplitude coupling that could exist, even in the absence of inhomogeneous broadening and, as we show, introduces enough of the physics of inhomogeneous broadening to reproduce the experimentally observed phenomenon.

The slave laser pump current is adjusted so that the free-running emission ($\varepsilon = 0$) is from the ES only. As with the experiment, the injection strength ε is swept in both increasing and decreasing directions, and the resulting intensities of the GS and ES are recorded. For each value of ε, the output from each state is constant. As seen in the experiment, a clear hysteresis cycle is obtained and is shown in Fig. 4. The agreement with the experimentally obtained cycle is clear. The injection induces a bistability in the system so that over a range of injection strengths the predominant emission can be from either the GS or the ES, depending on the initial conditions. Central to the findings is the parameter β which aims to account for the ES-induced phase-amplitude coupling. We introduce this parameter in a somewhat phenomenological fashion, but ascribe its origin to the inhomogeneously broadened QD medium. Its role is illustrated in Fig. 4. In the absence of inhomogeneous broadening, the possible outputs from a QD laser are no emission, GS emission only, ES emission only, and simultaneous GS and ES emission. For any set of control parameters, one and only one of these states will be stable. However, physically, one can see that inhomogeneous broadening may change this. In particular, for some set of control parameters, some dot populations may emit from the GS, while others emit from the ES. In this way, a bistability between dominant GS lasing and dominant ES lasing can be realized. The simulation results bear this out. The hysteresis loop does not exist in the absence of the ES-induced phase-amplitude coupling or for small non-zero values such as $\beta = 1$ [Fig. 4(c)]. The injection

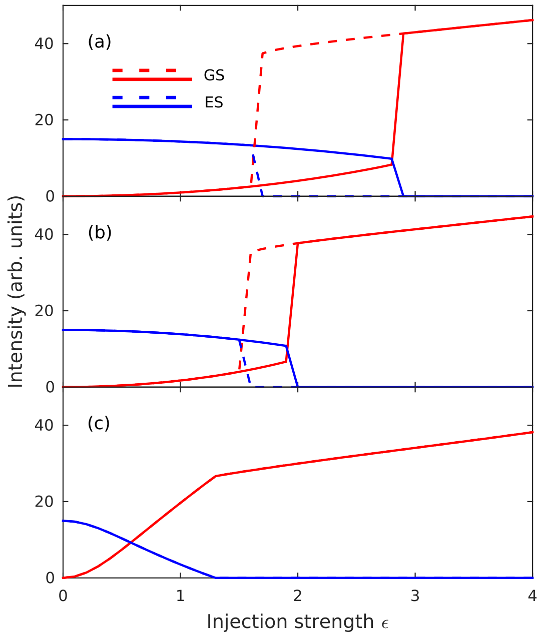

Fig. 4. Numerical simulations for different amplitudes of the ES-induced phase-amplitude coupling: (a) $\beta = 3$, (b) $\beta = 2.5$, and (c) $\beta = 1$. The traces show the GS (red) and the ES (blue) intensities versus increasing injection strength (continuous line) and decreasing injection strength (dashed line). The other parameters are $\eta = 0.01$, $\alpha = 3$, $g_0^g = g_0^e = 0.55$, $J = 20$, $B_{e,h} = B_{e,h}^w = C_h^w = 100$, $C_e^w = 10$.

strength increase leads to a gradual increase of the GS intensity, while the ES output correspondingly decreases. Hysteresis appears at larger $\beta \gtrsim 2$ [Fig. 4(b)] and becomes well pronounced for $\beta = 3$ as in Fig. 4(a). Extremely small pockets of dynamical instability may be pronounced at the point of GS switch off/ES switch on in the decreasing injection direction similar to the situation observed in the experiment.

In conclusion, we have demonstrated the existence of a bistability and a resulting hysteresis loop in an optically injected QD laser. Depending on the initial conditions, one can obtain emission from the GS or emission from the ES. The hysteresis loop is very large: the control parameter changes by a factor of almost five in the case shown in Fig. 3. This is significantly higher than the changes in control parameters in many other studies of hysteresis in laser dynamics such as those in [4]. We attribute the hysteretic behavior to inhomogeneous broadening modelled by an ES-induced phase-amplitude coupling.

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